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Assessing solar potential and battery instalment for self-sufficient buildings with simplified model

Marko Kovač [a, *], Gašper Stegnar [a], Fouad Al-Mansour [a], Stane Merše [a], Andrej Pečjak [b]

[a] Energy Efficiency Center, Institute Jožef Stefan, Ljubljana, Slovenia
[b] Institute Metron, Lesce, Slovenia

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ABSTRACT

The current governing economic policies and models are favoring maximizing overall solar panel power production in an effort to mitigate climate change. Those were adequate for relative low share of solar power within entire energy mix. As the share of photovoltaic energy production rises, those principles directly cause high mid-day summer productions peaks and even negative prices for the electricity, when solar power is in abundance. This prompts for different approach for calculating solar technical and economic potential, which can offer valuable data for planning future energy sources. This paper uses a simplified model to evaluate prevailing self-sustainable rooftop solar electricity production for typical households and micro-grids in combination with battery storage (Solar Plus). The used model is nevertheless covering most important features of solar power production: the weather pattern, load curves and roof orientation and can be used either for single home-owners or small businesses. Typical applications and main benefits of the assessment are discussed and critically reviewed. The used model is suitable for use on single households or house clusters in scattered populated area and was developed based on extensive empirical knowledge.

1. Introduction

Use of photovoltaic (PV) panels for the domestic self-powering is seen as somewhat disruptive technology for energy providers and home owners alike [1–4]. The first cannot afford the impact of many PV and especially summer daylight peaks, to disrupt the equilibrium of power grids, while the latter have limited information and experiences how is going to impact their overall costs [5,6]. Due to extensive PV support through feed-in schemes within years 2010 and 2013, the PV in Slovenia made quite an impact, covering an almost 2% of total electricity needs [7]. However, the number of installation was driven by the support scheme to mitigate the climate change and not by overall economics. From that period, the number of new PV installation has fallen significantly since more of the cost is now covered by home-owners and less by tax payers through the support schemes [7]. Rapidly decreasing PV prices are also improving cost efficiency of installation without the support schemes at the end-user level [5,8,9]. On the other hand, with the decreasing prices of battery storage, adding a storage unit to PV (e.g. Solar Plus) is quite affordable and viable option, which eliminates the main drawback of PV as an energy source – reliance on the daytime clear weather [5,10,11].

In the past a lot of quite refined models of PV efficiency were made (e.g., Refs. [12–15]), which by rule concentrated on maximizing the overall electricity gains from PV. However, due to that these models are less able to use different optimizing goal (e.g., self-sufficiency). Only recently a handful of academic analyses of PV instalments concentrated on other optimization goals such as minimal tariffs etc. [10,15,16]. On the other hand, home owners can use a wide variety of software tools alike ([17–19] with an extensive overview available in Refs. [20–22]), which would help them to choose complementary components for building a small-scale PV self-sufficient system. These approaches are quite sophisticated, however they might use a lot of parameters, which can affect the ability to find an optimal solution. Therefore, a somewhat simplified approach to model the PV energy input and battery storage in line with similar models (e.g., Refs. [14,23,24]), which should be suitable for the purpose while accurate enough, was used.

The used model is also suitable for quick but reasonable accurate

* Corresponding author.
E-mail addresses: marko.kovac@ijs.si (M. Kovač), gasper.stegnar@ijs.si (G. Stegnar), fouad.al-mansour@ijs.si (F. Al-Mansour), stane.merse@ijs.si (S. Merše), andrej@eauto.si (A. Pečjak).

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assessments of micro-grid instalments since the technologies (e.g., different types of electricity storage) and economic parameters are changing quite rapidly [2,25–29]. The falling prices of home PV and battery installations are pushing technology from the hands of tech-enthusiasts towards less energy issues knowledgeable investors, where quick (and adequate) models are essential to reduce the chances of costly misinvestments [30].

The main disadvantage of photo voltaic electricity production is its reliance to Sun daily and yearly motion, which could be mitigated by a storage system. While short term storage is economical feasible, long term (i.e., yearly) one is often out of the reach of common user [31]. Therefore, the effort on the improvement of PV efficiency should be on ensuring higher outcome in critical times, when the sunlight is sparse (i.e., winter in areas of moderate to extreme geographic latitude and/or bad weather) [32].

Fig. 1 shows the schematics of used model for calculating solar power and battery usage. The energy depends on PV and battery power outputs: The Sun position ω_{sun} (i.e., azimuth γ_{sun} and elevation α_{sun}), PV orientation ω_{PV}, the size and efficiency of PV panel (with incorporated efficiency of add-ons like inverter etc.), weather, local surroundings (e.g., shading), battery capacity, state and efficiency, household consumption (loading curve), outside and desired inside temperature (for heating), to name a few.

The main novelty of presented approach is the ability to properly adjust for rapidly changing technology advances and policy changes in a light of climate change mitigation. Therefore, a special emphasis was put on choosing only the significant parameters and disregarding others in an effort to keep the analysis as accurate and also as light-weighted as possible. This enables additional data or complexity (use of tracking PV panels, different types of batteries, even thermal storage etc.) to be easily accommodated. The model also allows interaction between micro levels (i.e. single house or house cluster) and experiences on the macro level (distribution of energy).

2. Model and data

The used model of household electric energy consumption and production is intentional simplified to obtain just rough indications regarding the most influential issues and shares similarities with REopt by NREL [33] and CoSSMiC [34]. While those are quite valid methodologies, they tend to apply top-down approach with strong role of distributers. Nevertheless, the proposed model shares governing equations with some similar models (e.g., Refs. [14,16,33]), the main differences are the selection and modeling of influencing phenomena, while keeping the number of parameters and/or degrees of freedom within managing scope.

The production of electric energy by photovoltaic is hence defined by time (due to orientation of the sun ω_{sun}, orientation of the PV panel ω_{PV}, solar radiation *sol_rad(t)* and also the battery storage level). The latter can fulfill the electric energy demand only if not thoroughly depleted. This also sets the goal used in the

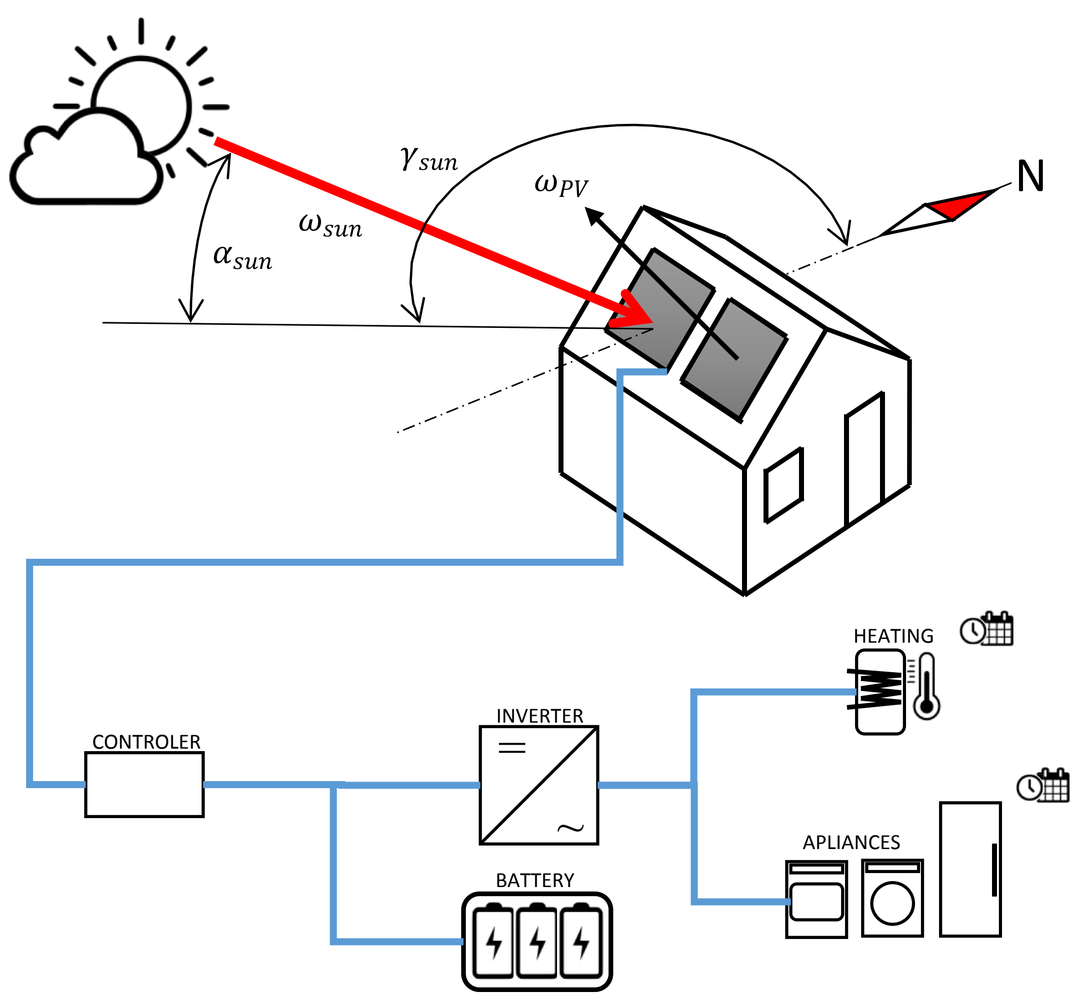

Fig. 1. Schematics of model used for calculating the photovoltaic energy production and battery usage.

optimization: the demand P_{demand} should be outweighed by sum of production $P_{production}$ and reserve from battery storage $P_{battery}(s)$ at any time:

$$\forall t; P_{production}(\omega_{sun}(t), \omega_{PV}, sol\_rad(t)) + P_{battery}(s) \geq P_{demand}(t, T) \tag{1}$$

The calculation of electric production from PV at the time does not account for shading, which needs case-by-case approach for each rooftop. Some ideas how to overcome this limitation are discussed and addresses in other literature [13,14].

Electric energy demand $P_{demand}(t,T)$ is a sum of general demand $P_{gen}(t)$ (e.g., lighting, home appliances), which varies over time of the day, and demand for heating $P_{heat}(T(t))$, which depends on the outside temperature (if that is lower than desired):

$$P_{demand}(t, T) = P_{gen}(t) + P_{heat}(T(t)) \tag{2}$$

$$P_{gen}(t) = P_{ave} \cdot \beta(t) \text{ and } P_{heat}(T(t)) = \cdot T^*(t) \cdot C^* \tag{3}$$

where P_{ace} is average demanded auxiliary power. Please note that thermal inertia of the house is not taken into the account. Thermal inertia has a tendency to shift the energy demand towards more PV favourable part of the day. Temperature deficit $\Delta T^*(t)$ and specific heating demand C^* are defined by:

$$\Delta T^*(t) = min\{T_{out}(t) - T_0, 0\} \text{ and } C^* = \frac{Q_{heat,year}}{\sum_t \Delta T^*(t)} \tag{4}$$

The focus of this research is to define the single minimum battery level $E_{battery\_min}$ over the whole year:

$$E_{battery\_min} = min\left\{P_{battery}(s)\Big|_t\right\} \tag{5}$$

This approach is somewhat different from other approaches, such as [35,36], where the overall minimum sum of energy was observed. This is due to the different fail-mechanism for self-sustainable houses or clusters defined in eq. (1). To accommodate different types of energies (e.g., heat), the separate set of equations is needed with proper intermediate relations.

2.1. Parameters

For the purpose of this paper two households were analyzed. The location of Ljubljana, Slovenia was used for the purpose [37]. The main reasons for particular location are availability of the data and the somewhat demanding weather pattern, with relatively cold and cloudy weather during late fall and winter, which impairs PV electric production and enhances demands for the battery storage. Fig. 2 shows outdoor temperature (left) and solar radiation (right) for the modelled reference year [38]. This takes into account measures of selected parameters in the space of 30 years and thus presents historical digital data set that represents measured 365-day values of the selected meteorological variables on the hourly basis. The sequence is synthetically constructed using monthly values selected from a multiple year data set for a given location so the resulting test reference year is typical for the location. The annual energy demand was acquired from Tabula web tool [37], which has data of real buildings. Hourly demand was calculated as a linear function of temperature deficit, however no additional sources (solar radiation and internal heat gains, transmission and ventilation losses) were taken into account due to simplification.

The calculation of solar position was adapted from the calculation procedure by NOAA [39,40]. An optimal position of photovoltaic panel with maximum total energy output for selected location is elevation of 32° and azimuth of 178° [41]. However, this approach with relatively narrow spikes in solar electricity production causes duck-curve phenomena [2], which averts even wider acceptance of photovoltaic and hence renewable electricity production.

Fig. 3 shows solar hourly values of solar radiation for January (left column) and July (right column) for flat (top row, elevation of 0°) and elevated (bottom row, elevation angle of 64°) as a heat map. The days are indicated on *x*-axis (going from 1st to 31st) and the hours on y-axis (from 0^h to 24^h). The weather data for model year for chosen location was used [38]. The scale (right) shows the values of radiation ranging from 0 to 1000 W/m^2.

The top row shows the sharp difference between the winter and summer radiation on a flat surface. Therefore, a suitable PV system for the winter will be quite oversized for the summer. In the bottom row the winter heat maps shows a lot more sun energy is caught by the elevated panel with a relative small impact in the summer. This also means that the yearly difference for elevated PV panel is a lot smaller than for the flat one.

Nevertheless, some type of power storage is necessary to cover daily, weekly or even seasonal needs. The current norm of PV small-scale operators is to use the power grid as a storage device. However, with rising prices of power grid fees, the push towards electric energy independence will grow further [2,27,28]. In this case PV panel should be assisted with batteries (Solar Plus concept), which are rapidly gaining popularity.

2.2. Time-step

A time-step is quite important part of the model – too sparse and important phenomena will be lost, too dense and number of

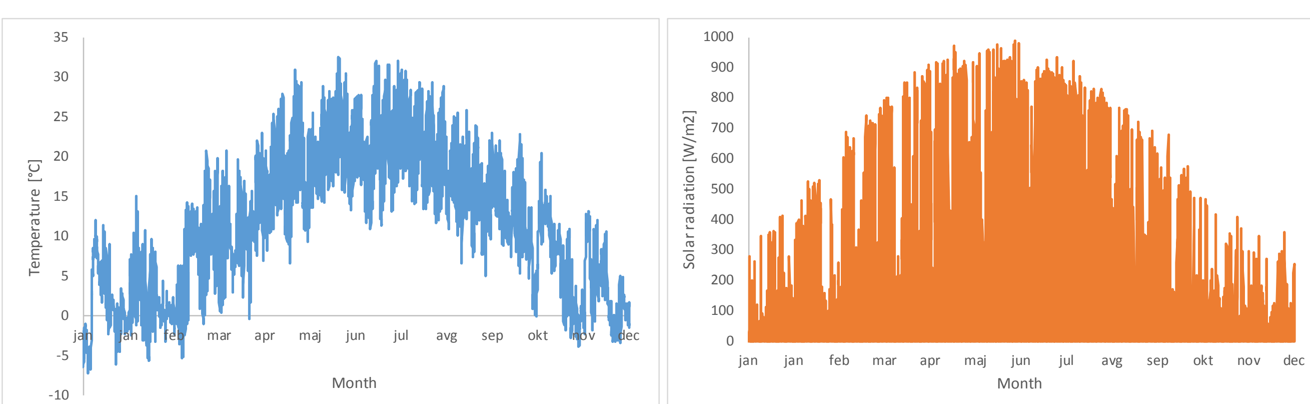

Fig. 2. Outdoor temperature of selected model year (left) and solar radiation on a horizontal surface (right).

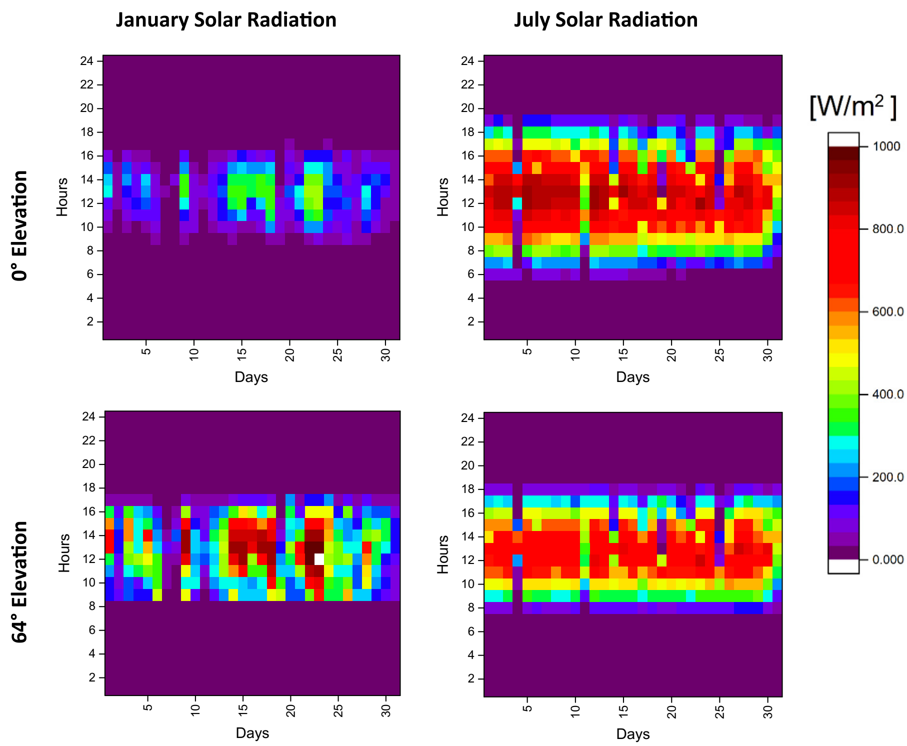

Fig. 3. Solar radiation on horizontal (top row) and elevated surface (bottom row) in January (left column) and July (right column).

calculations can be rather high. Fig. 4 left and right show the typical daily household power structure with PV and battery with 1-min time-step metering and 1-h time-step metering, respectively. General household demand in combination with source of energy (PV or battery) can be observed. The data was obtained during CoSSMic project [34] from a household in Konstanz, Germany for a period of 155 days and was averaged over that period. The graph clearly shows expected bigger volatility of data, with a time-step of 1 min (left) compared to data with a time-step of 1 h (right).

Usage of 1-h period can be rationalized by the latest experiences with battery supported power grids, which shows extremely quick response to fluctuations in energy production and demands [42]. Furthermore, the battery capacity is large enough to easily accommodate even the largest domestic loads over the period of the scope interval. Therefore, 1-h time-step was used for the calculation, which also corresponds with the availability of meteorological data.

2.3. Verification of the model

To results of the model were compared to results of well-established commercial software and also to real data of energy production from several power plants. For the first part we used IDA Indoor Climate and Energy 4.8 [43]. The weather data was obtained from ASHRAE 90.1 extension for model year within period 2000–2010, which has some differences compared to the used weather data [38]. Fig. 5 shows monthly sums of solar power results two verification cases: a horizontal one with elevation angle of

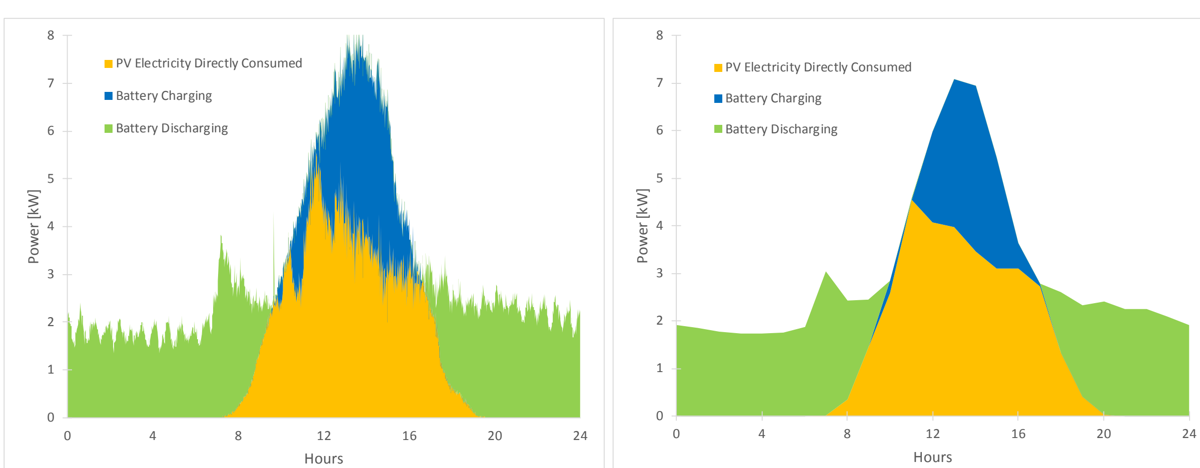

Fig. 4. The typical daily household power structure with PV and battery. Left side shows 1-min time-slot metering and right side 1-h time-slot metering.

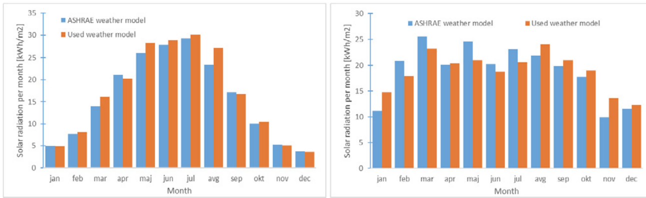

Fig. 5. Monthly sums of solar power from two panels with different elevation angles: horizontal (left) and angled for 64° (right).

0° (left) and an elevated one with elevation angle of 64° (right).

The results show that there is a high level of agreement between the models for both orientations and some differences can be contributed to the mainly different weather data. The Ashare model (blue) predicts a bit sunnier weather in the first part of the year, while the used data shows larger outcome in the second part. The differences in power output are also a very good indication about the sensitivity of the weather models.

In addition the model was tested against aggregate data from several rooftop solar power plants from Ljubljana, Slovenia with only power plants with all year-round data were considered [44]. The weather data for year 2015 was used [38]. To account for loses due to shading of geographic features (e.g., near-by buildings and vegetation or terrain) is usually assessed on case-by-case basis. Since those tasks to determine real skyline are quite demanding, an averaged linear value, which is easy to incorporate into equation (1), was assumed. This approach might be to crude for single household analysis, however proved quite efficient in case of 250 different PVs [44].

Fig. 6 left shows monthly correction due to lack of PV production while the sun is below skyline, since weather data for solar radiation does not account for shading. This phenomenon is negative and more pronounced in the winter and can effect electricity production up to −25%. In our case, an elevation of 10° proved to be efficient enough. The results of the PV electricity production were also adjusted to accommodate for roof and hence PV panel elevation.

In addition, the solar radiation data [38] also does not account for PV orientation (i.e., azimuth and elevation), while solar plants data does not include data on particular installment elevation. A quick sensitive study was therefore performed regarding effect of PV orientation, where it was assumed that majority of considered PV installations were close to the optimal elevation angle for Ljubljana of 32° and azimuth of 180° [41]. The results of monthly correction are shown in Fig. 5 right, where first number in legend regards to PV azimuth and second to elevation. The effect is mostly positive and again quite substantial in winter. The effect is less sensitive regarding changes in azimuth and more regarding elevation – with small sacrifice in summer production we can ramp-up winter efficiency.

Fig. 7 shows the data obtained from existent rooftop PV installations for Ljubljana in 2015 on monthly basis. Solar radiation (thick orange line) is obtained from meteorological data [45] and solar power plants production (green line) from the power plant database [44]. Gray shaded heat map shows the histogram of all the data in the sample. The blue dashed lines are showing the solar production with corrections (due to roof elevation or shading). Finally, the red line shows the results of solar production with both corrections accounted for.

The results show that effects of shading and orientation (especially elevation of PV panels) play an important role in overall energy efficiency of rooftop PV systems. Nevertheless, used approach shows good correlation with existent empirical data.

This in addition to comparison to well-established models enables the validity of the model and allow additional simulation of those phenomena and hence better understanding.

3. Using model on a single household

Two showcases are used for model demonstration on a single household – see schematics in Fig. 1 [37]:

(a) A small cabin with area of around 50 m^2 and general electricity needs (for lights, home appliances, entertainment etc.) of 2500 kWh per year and energy needs for heating of 1000 kWh per year and
(b) A normal passive residential house with area of 150–200 m^2 with general electricity needs of 3000 kWh per year and energy needs for heating of 2500 kWh per year.

The showcases were calculated using a PV panel ranging between 3 and 15 kW_{el} and battery storage with capacity of 10–100 kWh, which at the beginning of calculation was holding a half of its capacity. It was reasonably assumed that the discharge current capability of the used battery storage is sufficient to power the household at any time.

Fig. 8 left shows an averaged demand for electricity in households relative to average consumption [46] – noted as $\beta(t)$ in equation (3) plotted against daily hours, where the morning and afternoon/evening peaks are clearly visible. Some resemblance with demand curve shown in Fig. 7 can be observed – two demand peaks: narrower in the morning and the wider in the afternoon. However, two peaks are at different time (biggest difference is at the latter peak), which can be explained by untypical type of

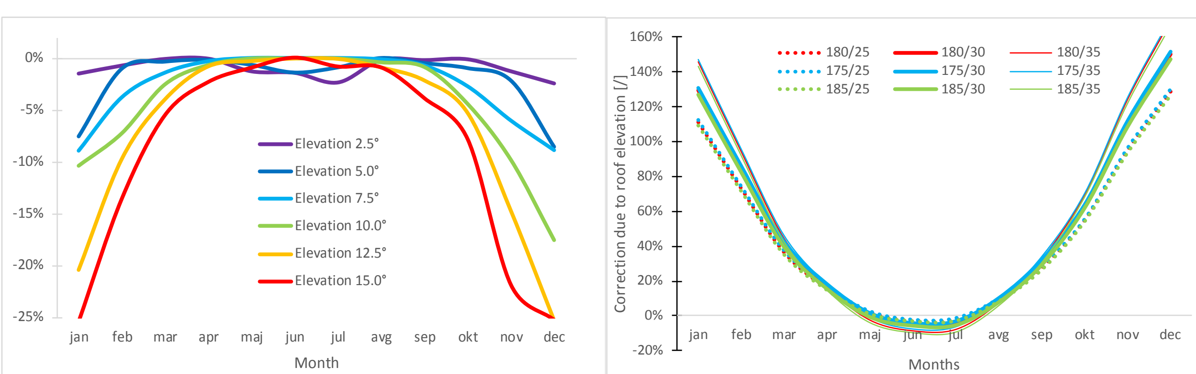

Fig. 6. Correction due to Skyline elevation (left) and PV orientation(right).

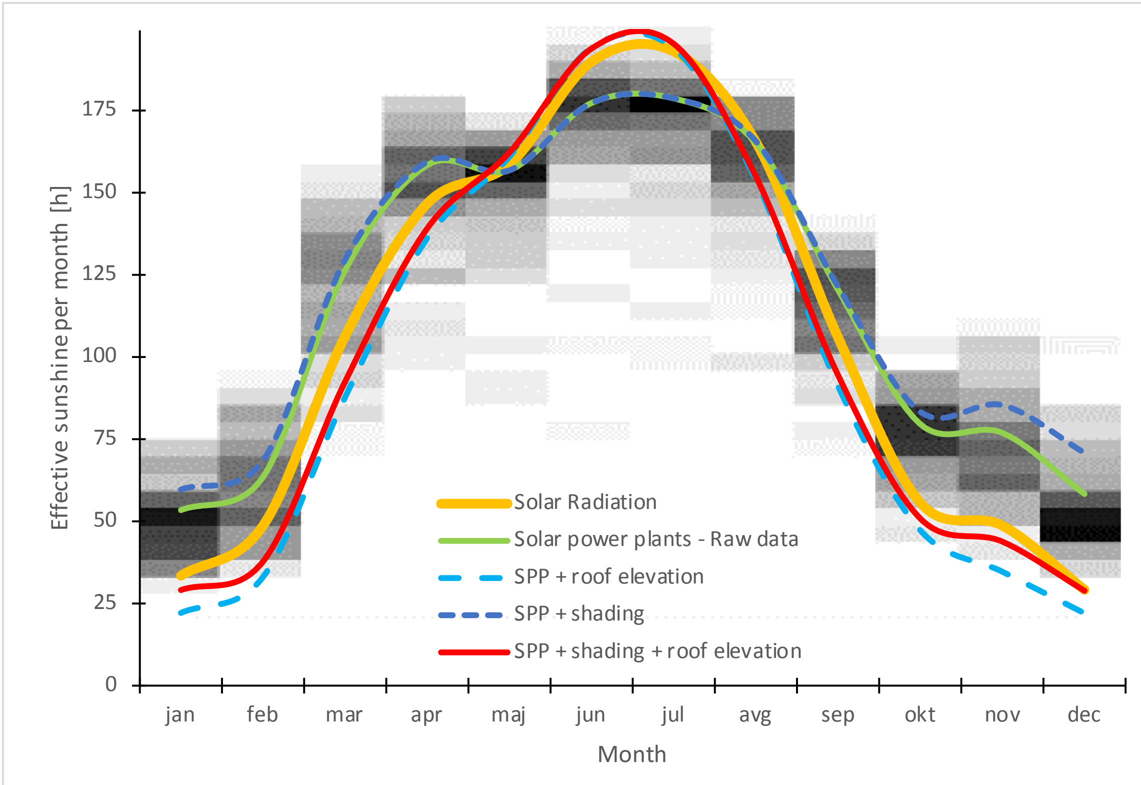

Fig. 7. Solar radiation and power plant electricity production.

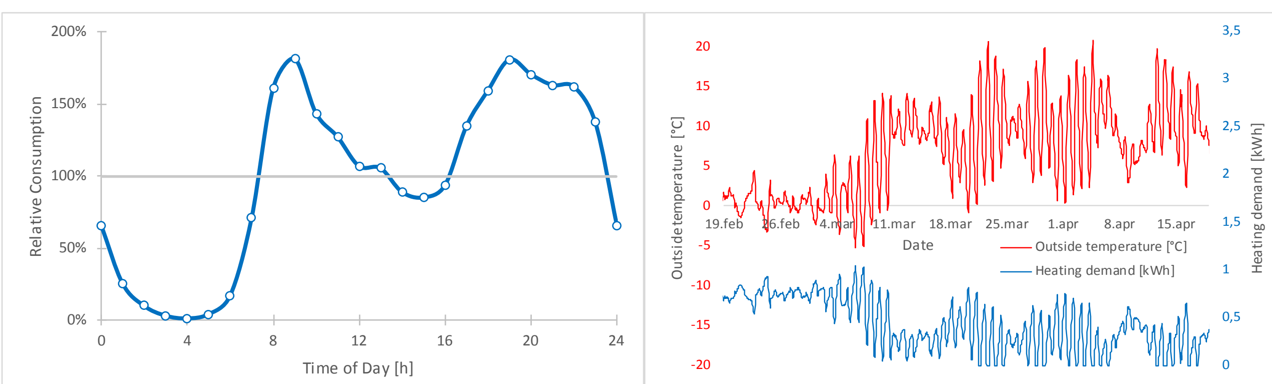

Fig. 8. Relative electric energy consumption (left) and outside temperatures and temperature deficit (right).

household in Fig. 8. Unfortunately, due to strict privacy laws, the household type (e.g., farmhouse, city house) could not be obtained. If usage of electricity demand seems intuitive, some authors had rather used the tariff curve to optimize production from PV panels [47]. This might be useful, when optimizing household electricity production for profit, however our aim is to optimize to have zero energy import. Furthermore, the tariff curve should eventually shift to be closer to production-demand curve, which already happening on the wholesale markets [48].

Fig. 8 right shows the outside temperature (red line, left-side scale) and heating demand $P_{heat}(T(t))$ (blue line, right-side scale) for 60-day period of model year – from the late February to the late April. The demand for heating noticeably decreases as outside temperatures start to rise due to the Spring weather.

Fig. 9 shows typical result of the proposed model for a set combination of PV panel size and orientation and battery storage capacity. The PV has area of 80 m^2 with azimuth of 177°, elevation of 64° and installed power of 12 kW_{el}. The battery storage has a capacity of 60 kWh with inverter roundup efficiency of 80%. The model shows three occasions, where particular combination will not fulfil the household energy demand. This is shown in Fig. 9 as the battery storage level dropping below 0 kWh. Although the storage level cannot drop below zero, this indicates that at that time, the household power demands outgrown the sum of energy in storage and possible PV production and could cause power outtakes of several hours or even days.

The zoomed area shows hour behaviour – when the sun energy is enough, the PV panels fills up the storage before the sunset,

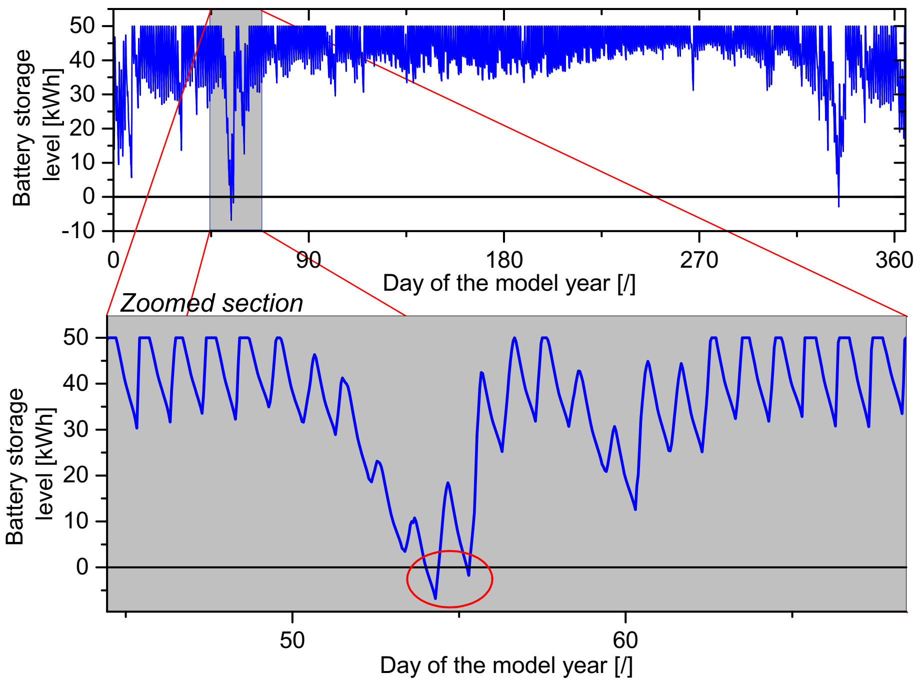

Fig. 9. The result of the model shows the battery storage level over the model year (top). The greyed section is zoomed at the bottom, where battery storage level dips under 0 kWh.

which can be observed as clipping in the data. However, when there is not a lot of sunshine, the energy demand depletes the battery reserves without filling them during the day. The absolute minimum can be seen during the night between days 54 and 55 (i.e., February 23rd and 24th, indicated with red oval in Fig. 9) The minimum battery storage level seems like a good enough indicator if our self-sufficient system is constructed well. On the other hand, the choice of the minimum battery level means that the model is quickly becoming complex (i.e., eq. (1) becomes non-differentiable function), which can still be controlled at the single house level with modern numerical methods, however it becomes cumbersome for multiple-house clusters.

To expand the results of the model shown in Figs. 9 and 10 shows that minimum of calculated showcases (a) and (b), respectively as an influence of area of PV panels (x-axis) and battery storage capacity (y-axis). Only marginal situations with minimum battery levels between −20 and + 20 kWh are shown in color. The areas with a large energy deficit are shown in gray and areas with energy surplus are shown in white. The thicker black line indicates situations, where PV panels and battery storage are just enough to enable 100% energy delivery (according to the model). Negative results are sign that the whole combination of PV facility and battery storage are not enough to cover the energy needs. The minimum usually occurs during longer times of bad weather during winter periods.

The results show that the energy self-sufficient household can be achieved using proper combination of PV panels and battery storage in a combination that offers lowest price while self-sufficient. The case (a) as typical yet passive residential house needs about 85 m^2 PV panel (which is roughly equivalent to 13

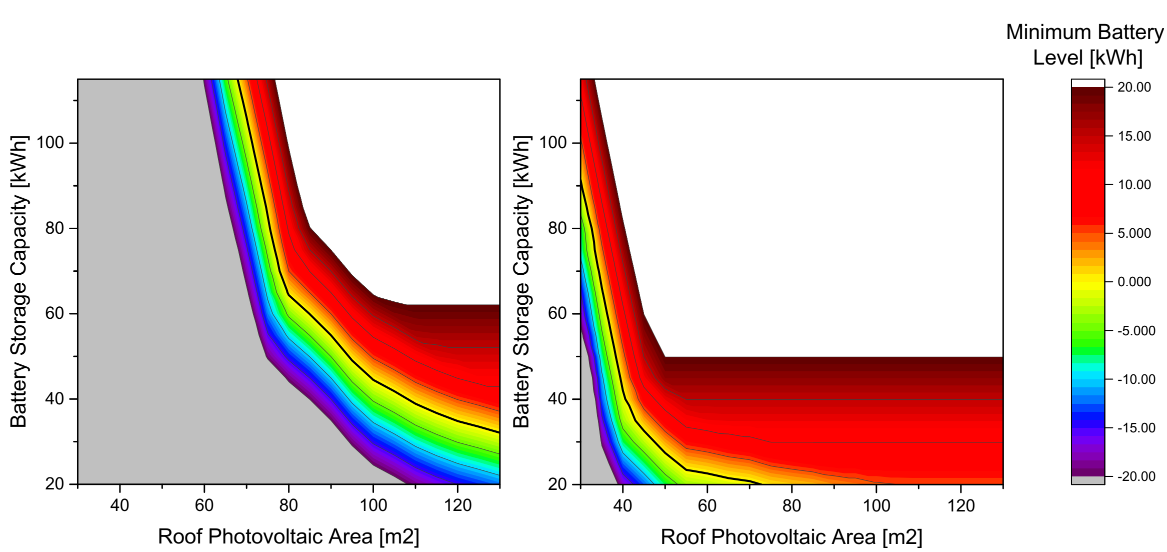

Fig. 10. The minimum battery level of calculated cases (a) – left and (b) - right.

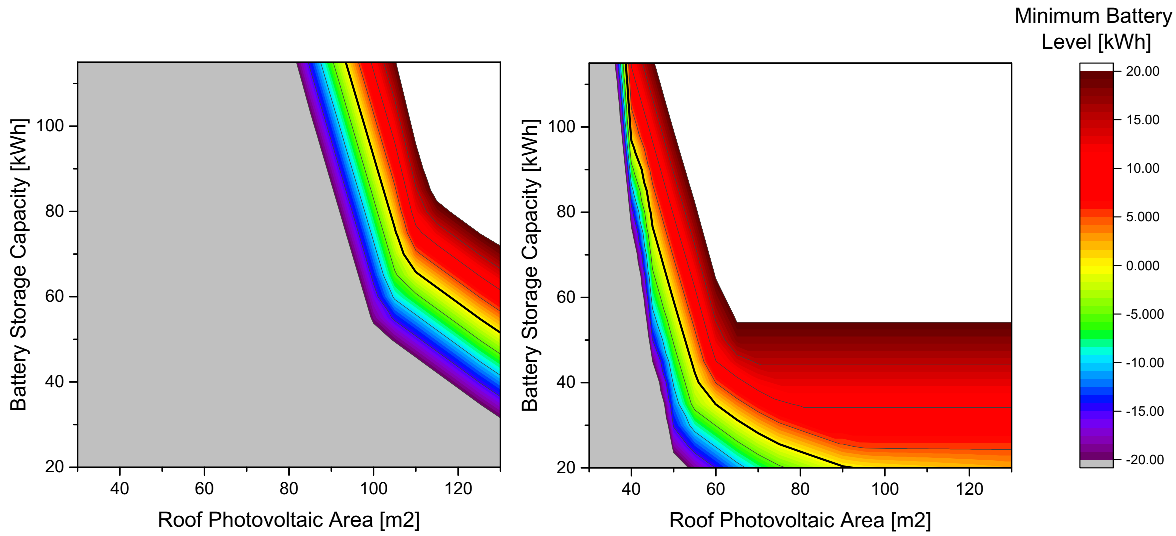

Fig. 11. The minimum battery level of calculated cases (a) – left and (b) – right with shading elevation of 10°.

kW$_{el}$) and 60 kWh of battery storage. The case (b) of country cottage shows the needs of 40 m^2 PV panels (6 kW$_{el}$) and 40 kWh of storage. This means that any other combination with larger capacity of PV panels and/or battery storage will enable enough energy to provide for a calculated household.

If the effect of shading, as shown in Fig. 5, is also accounted by the model, the results shift – more PV panels and battery storage is needed. The case (a) now needs about 110 m^2 PV panel (roughly equivalent to 16.5 kW$_{el}$) and 70 kWh of battery storage. And the case (b) needs of 50 m^2 PV panels (7.5 kW$_{el}$) and 50 kWh of storage. The shift towards greater needs is also shown in Fig. 11, which shows cases (a) and (b) with 10° of uniform shading. The visualization shows that the shift is more pronounced towards greater PV panel capacity than greater battery storage.

To evaluate the economics of sunroof PV panels, an expense obtained was obtained from reports such as [27], with the current prices of installed battery storage are around 325 €/kWh for small units (up to 50 kWh). The prices for PV installation up to 50 kW$_{el}$ are around 1200 €/kW$_{el}$, which covers the cost of modules and installation. Using those price assumptions, the different combinations presented in Figs. 9 and 10 can be estimated for cost. Fig. 12 shows minimum battery level plotted against installation costs for both showcases (a) and (b). The approximation curve that connects most optimal examples is shown with coefficient of determination R^2-values. This approximation shows that the cost of self-sufficient installation of PV panels and battery storage for typical household (showcase (b)) are in order of 32,000 €. For somewhat smaller house (showcase (a)), the price of installation is around 17,000 €, which is in accordance with expectation since the total energy consumption of typical household is almost double the small cottage.

However, the cost of installation is not the only cost to determine levelized-cost-of-energy (LCOE), since it does not cover the maintenance costs and also due to different lifespans of PV panels and batteries [2]. The lifespan of former is around 25–30 years, the lifespan of the latter much depends on the number of cycles and wholesome energy throughput. The presented cases had 400–525 battery cycles per year with the cumulative energy flow of 4.6 MWh. Based on data from literature [49] and from some of the manufacturers [50,51], the expected economical lifespan varies, however an assumption of 12 years is reasonable. This means that batteries storage will have to be replaced an additional time.

Based on that calculation, the lifetime costs are 32,000 € and 17,000 € for showcase (a) and (b), respectively. LCOE is therefore 0.32 €/kWh and 0.25 €/kWh for showcase (a) and (b), respectively. These costs are quite high compared with momentary cost of

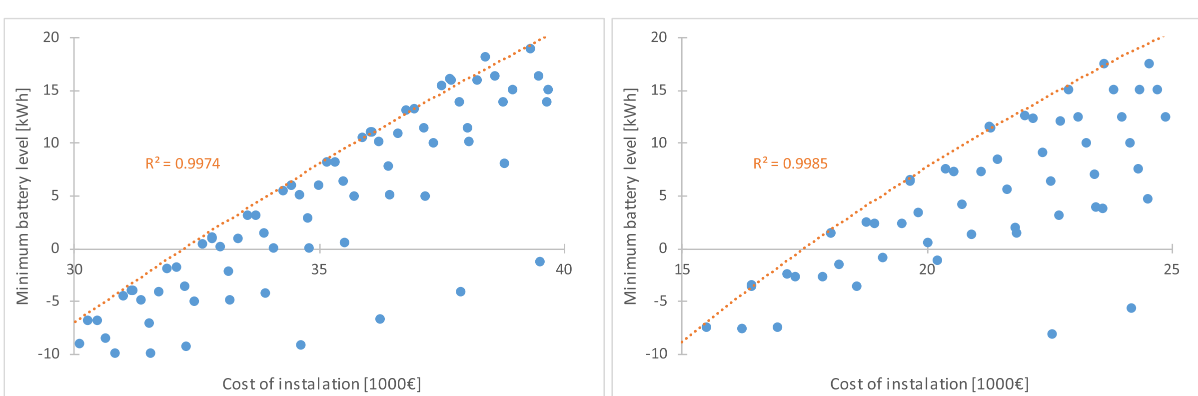

Fig. 12. Minimum battery level plotted against installation costs for showcase (a) on the left and showcase (b) on the right.

energy. The main reasons are still relatively costly PV panel and battery storage infrastructure and absence of net metering (the model assumes that the overproduction of energy is at the moment discarded).

4. Using model on a house cluster

Due to somewhat scattered population in Slovenia with small villages, where villages up to 30 houses represent around a third of Slovenian village count [52], the micro-grid solutions, where several close-by houses or objects are connected and equipped with renewable source of energy. This also offers a reasonable extension of the proposed model. Fig. 13 shows schematics of house cluster with battery storages in homes (stationary) or/and electric vehicles.

The properties of a house cluster are [30,32]:

- It has 5–30 houses (each inhabited with one or two families).
- The micro-grid includes at least one workshop or a private enterprise such as restaurant etc.
- Electricity storage is implemented in EV and stationary batteries.
- Interconnected with (macro) grid with its operator switching on and off larger energy consumers and producers.
- Virtual grid connection possible (e.g., filling EVs at work).

EV driving behaviour was obtained from report [53] and shows that the majority of EV users is using EV daily with charging habits of 80% at home and 20% at work (only marginal share of charging occurs on charging stations mainly due to long trips).

There are some important differences between single house and used house cluster models. The scheduling of each house are not synchronized. This can distribute the loading peaks around. In the current model, we have also used EV for electricity storage. This is handy, since an average vehicle is use around 5% of the time, but also complex, since during the day, the vehicle might be parked at other location (i.e., work). If the work location is physically out of the micro-grid. A virtual grid could be established through the connection to the main power grid [30].

The house cluster is assembled from multiple different households and a shop. The energy demands are also not uniformly

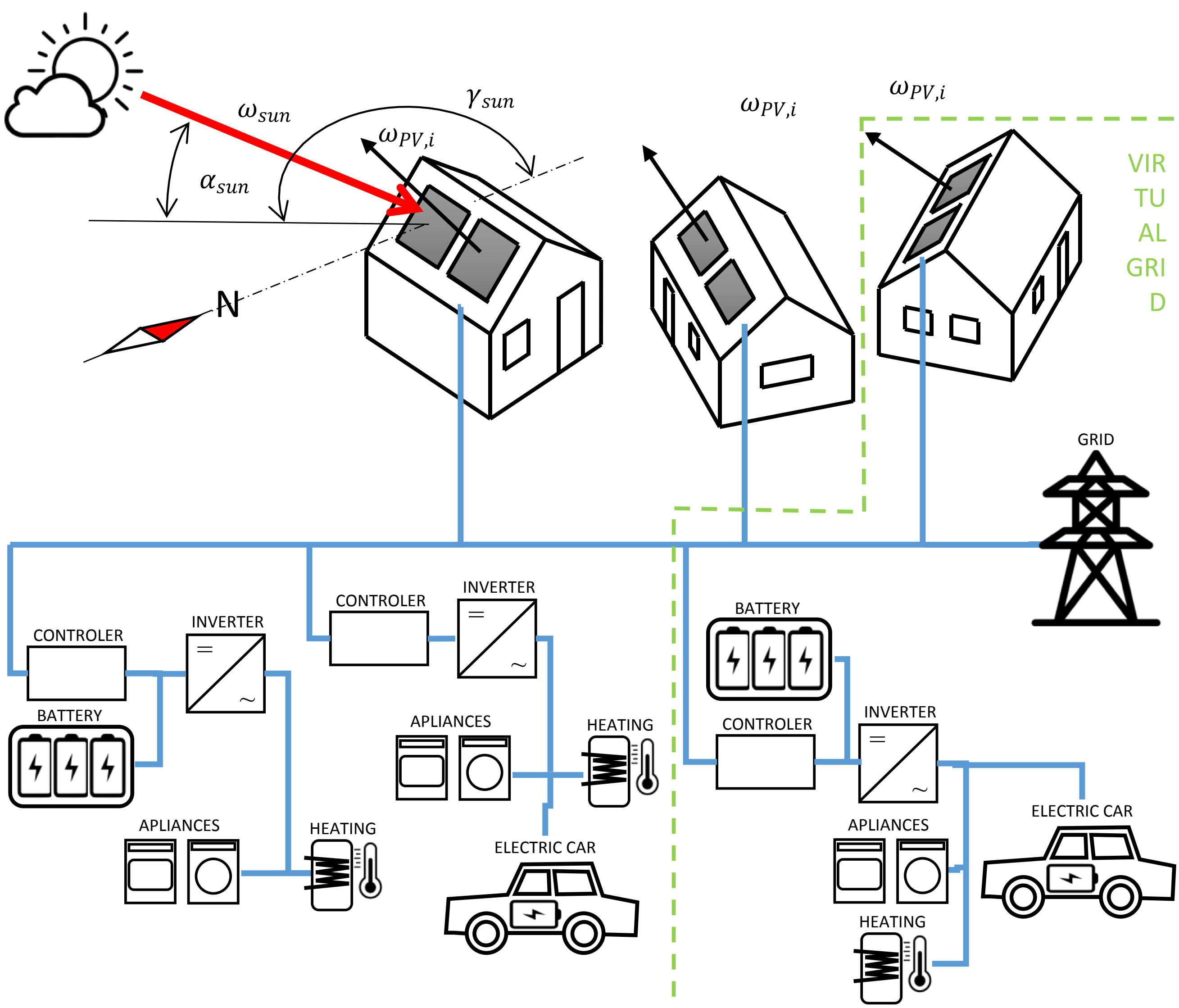

Fig. 13. Schematics of a micro-grid of a house cluster.

scheduled but are randomly time-shifted. Fig. 14 shows shared energy demands in single house (blue line), shop (green) and house cluster (orange).

4.1. PV panels orientation optimization in house cluster

Multitude buildings in house cluster and hence multiple possible different orientations of PV panels might contribute to increase in total PV yield. However, even simplified model as used in our research proved quite a challenge for optimizing. Namely, adding additional PV panels to out electric energy production facilities ads even more optimizing parameters or degrees of freedom (DOF). Each additional PV panel is defined by orientation (i.e., azimuth and elevation) and area (relative values were used to allow for comparison with single house solution). Solving numerical solution proved extremely difficult also due to discontinuous function of our model, which prevented usage of some well-established numerical methods (such as relaxation).

Fig. 15 shows yield in minimum battery level in relations with number of houses and hence PV panel orientations. NOMAD solver [54] was used to obtain optimal solution, however it began cracking down, especially with increasing number of PV panels and hence the parameters. This might indicate that additional yield due multiple PV panels is small and/or the limitations of used solver method with

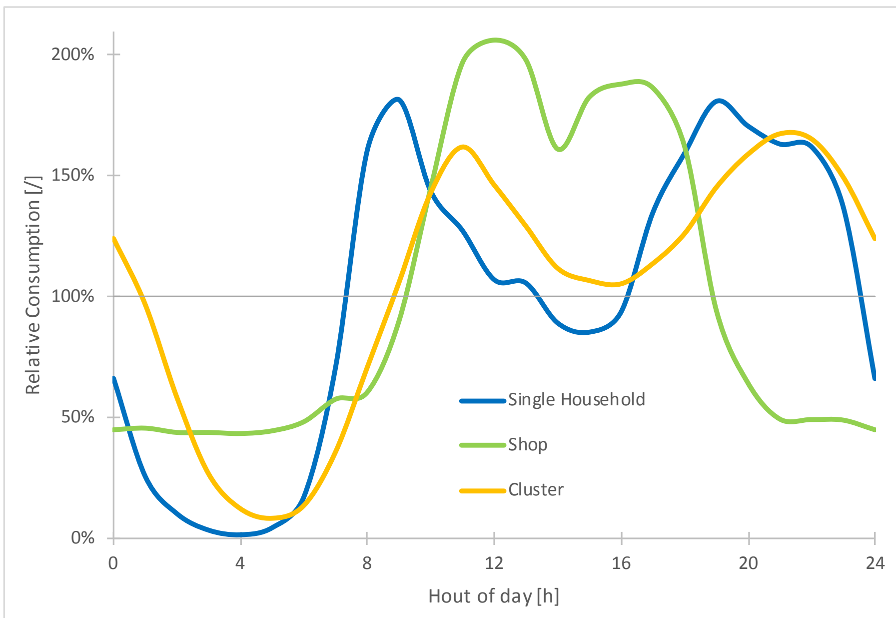

Fig. 14. Effect of multiple households on averaged house cluster energy demand.

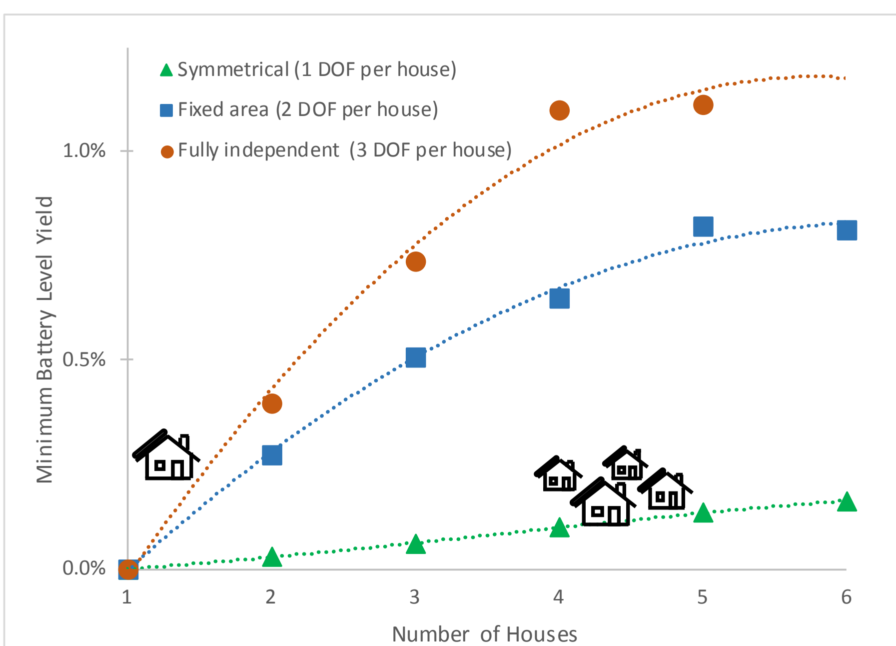

Fig. 15. Effect of multiple households on PV panels orientation.

highly non-linear and discontinuous functions. Some other authors [35,55,56] reported much more success with other optimization schemes, however our evaluation is that the somewhat undesirable results (please note a sharp deterioration of results when combined number of DOF exceeds 10) is mainly caused by our self-sufficient criterion cited in eq. (1). Nevertheless, the solver method will be further investigated and upgraded in the future.

The obtained yields, regardless the number of households and type of optimization, are quite small, however one can observe some trends. Based on the extrapolation of obtained calculation, we can predict that for 30-house cluster the yield of PV panels could be 10–20% larger compared to single roof system, which is also in-line with known results of cluster optimization [35].

4.2. Electric vehicle energy storage

Another practical issue, which can have large impact on the results of multi-household clusters is energy storage in EVs (Vehicle-to-grid or V2G concept, [57–60]). Due to range anxiety, the batteries in EVs are usually larger then needed, which means they store more energy, which could be used as a reserve (much as stationary battery) [61,62]. However, the normal behaviour shows that EVs are in usage (or rather at other location) during daytime, when (household) solar energy production is at its peak [53]. In that case only small amount of EV storage can be also used as a household storage. In addition, this makes economic sense only if charging at work in on charging stations is cheaper than overnight storage, which at the moment might not be the case due to relatively complimentary night tariffs. Nevertheless, the future tariffs are hard to predict and calculating economic sense in such a dynamic scenario proved complex [63].

One of the solution to how to maintain EV as a part of electricity storage is introduction of virtual grid, where EV can be charged during the day whenever there is a grid connection. This also means that integration of micro-grid into national (or at least wider) grid is indispensable. In that case the battery in EV behaves like a stationary battery with consumer paying for additional grid service.

Fig. 16 shows household battery storage level in the first 35 days of modelled year with different EV scenarios (connection to grid is also taken into the account):

(a) Home storage with battery capacity of 60 kWh without EV (blue line).
(b) Home storage with battery capacity of 40 kWh and EV capacity of 20 kWh, the car starts in the morning with full storage and returns empty in the evening (green line).
(c) Home storage with battery capacity of 20 kWh and EV capacity of 20 kWh, the car starts in the morning with full storage and uses 5 kWh one way (this is rough equivalent of 30 km at average consumption 17 kWh per 100 km). It uses virtual grid to connect to home facility and charge the EV even when note at home (red line).
(d) Home storage with battery capacity of 40 kWh without EV (yellow line).

The results of different scenarios plotted in Fig. 16 show the disruptive nature of EV due to its moving nature. Hence the most favourable scenario is (a), blue line, where there is no EV in the system. Worst scenario seems (b) green line, where EV battery is usually not available but furthermore we use domestic energy to charge EV. This solution is even worse than scenario (d), yellow line, with reduced battery storage, which suffers from small battery capacity. The state of scenario (c) – red line, seems changing. When there is a lot of solar energy available, this scenario is rather good and almost touching scenario (a) with no EV. However, when solar energy is sparse, the effect of virtual grid is not so pronounced. The difference between cases (b) and (d) is that we can use surpluses of electric energy (please note that Fig. 16 shows mostly January of model year) and charge EV with it. The presented results show that

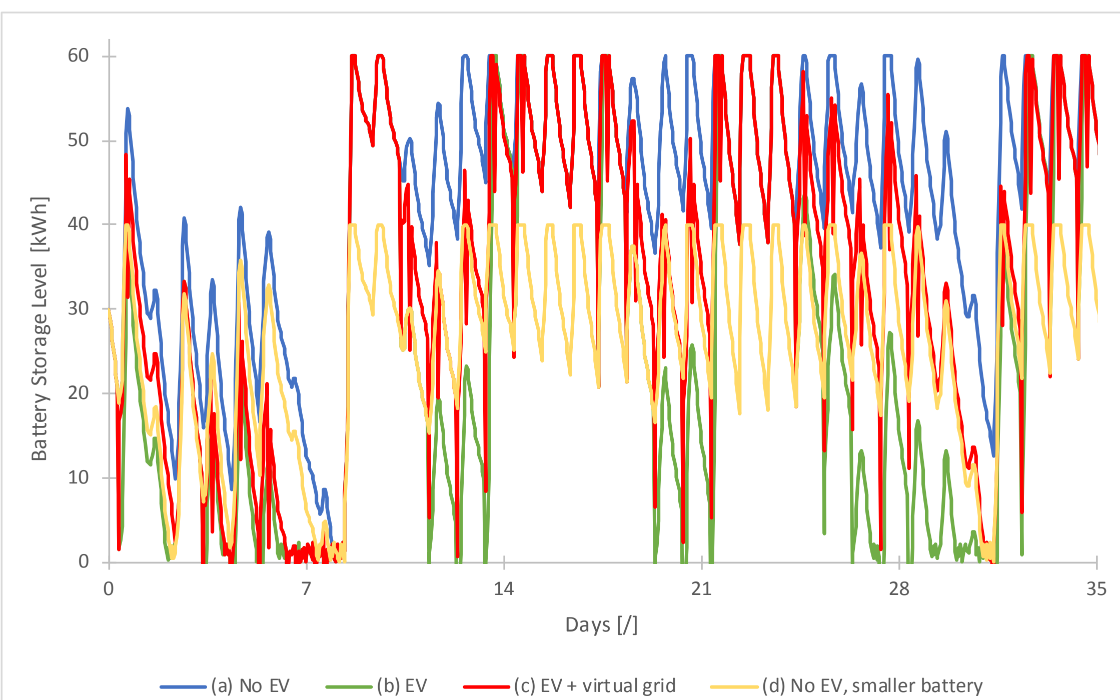

Fig. 16. The battery storage level in first 35 days of modelled year with different EV scenarios.

incorporating EV batteries might improve battery storage levels, however large effect is only achieved with grid connection.

4.3. Grid connection

Usage of real data (such as household demands, yearly climate and temperature data etc.) shows that somewhat simplistic approach with using yearly averages has some drawbacks. On the other hand, usage of quite complex models increases accuracy and intricacy beyond usability. As somewhat demonstrated in Fig. 9, the success of particular combination of PV panels and battery storage depends just on several weeks or even days in a whole year. However, these critical days' demand beefing-up electricity installation, which could be referred as the-last-kWh problem. The data shown in Fig. 9 can therefore be upgraded with calculation of how much the household/cluster installation could be decreased if small share of electric energy is provided from the grid and is shown in Fig. 17.

Even reasonable share of grid energy (1–5%) can lead up to 20 m^2 smaller needs for PV panels and 20 kWh less storage needs for battery capacity. This of course has effects also on the initial investment and LCOE, which is shown in Fig. 18.

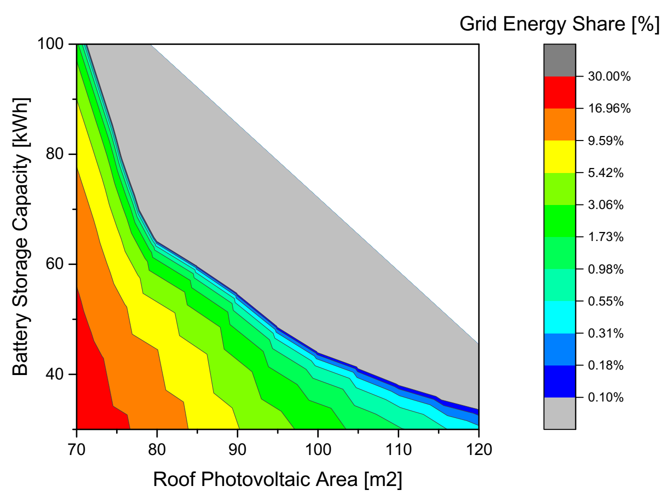

Fig. 17. The effect of grid share to the roof photovoltaic area and battery storage capacity.

The results of the model show that even 1% energy reliance on the grid can drop the initial investment price in order of 10%. A grid electricity share of 10% could lower the initial cost for 10,000€ and LCOE for almost 0.15 €/kWh. The results of the model show, that self-sufficient buildings are quite expensive and only make sense in a gridless area, where the costs of building the grid is higher than the price of PV panels and battery storage. This is also in accordance with some small-scale empirical tests [30,32,64]. This discussed cases also showed that used simplified approach is suitable for straightforwardly incorporating additional features (shading compensation, V2G, additional grid connection etc.)

5. Conclusions

The paper discussed assessment of the used simplified model to calculate self-sufficient or near self-sufficient household PV installation and battery storage combination (i.e., Solar Plus). The model, which accounted for per-hour household electricity and heating demand and also calculated PV panel yield based on per-hour data in moderate climate, used also some significant simplification (e.g., no PV output decay, no effect of temperatures on PV yield and climate change due to sunnier days). Nevertheless, it showed useful accuracy for predicting the household and house cluster energy behaviour. The results of the model were verified against well-established software tool and also empirical data of 250 solar power station, which showed reasonable agreement.

The paper at first discusses two cases, where a simplified model was used to determine optimal combination of PV panels and battery storage for different type of buildings – a residential house and a small cabin. The model is then extended to incorporate more houses (house cluster), vehicle-to-grid storage and grid connection for optimizing the installation and energy cost further. The model showed reasonable suitable, with some additional optimizing effort needed with larger numbers of houses.

The discusses example also showed suitability of Solar Plus approach for usage on houses. The optimal panel elevation for specific case was calculated, which helped to bridge the difference between summer and winter solar gains. The results show the large differences between orientation of PV panels (especially their

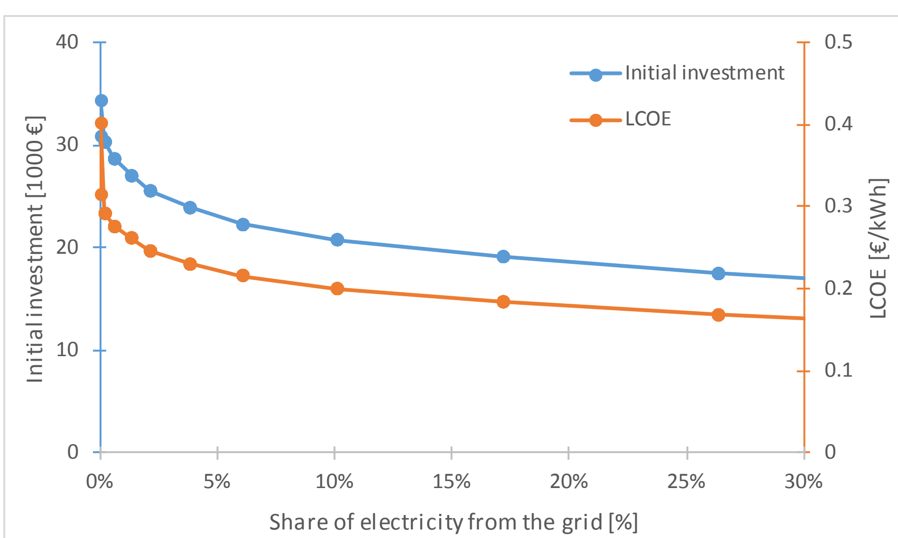

Fig. 18. The effect of grid electricity share to the roof photovoltaic area and battery storage capacity.

elevation) in regards with net-metering approach, which does not account for PV energy surpluses. The proposed approach for assessing and optimizing self-sufficient buildings seems suitable for dispersedly populated rural or sub-rural areas, with scarce grid connection. The optimum elevation in that case was around 64° (compared with 32° for optimal net-metering output), which perhaps also encourages integrating PV panels into façades and windows.

In addition, some indicative econometric parameters were calculated - the installation costs and levelized-cost-of-energy (LCOE) were calculated. The installation costs for energy self-sufficient living house is in the order of 32,000€, while LCOE is 0.32 €/kWh. These prices are high, which corresponds to general wisdom in house-building in Slovenia. However, additional usage of the model on house clusters showed that those costs can be significant lower if multiple houses with different demands and also PV panel arrangement are concerned. However, the model also shows clear price benefits for wider electricity grid connection. The LCOE can get to less than 0.20 €/kWh with 10% of grid dependence price of electricity. This approach also shows some possible directions for electricity grid development in Slovenia, with specific wider spread settlement.

The aim of the demonstrated approach was to show how to build the model, which could in the future interact with other energy savvy solutions as for instance thermal storage or wind energy. Those single energy source models are quite accurate but they fail to provide simple answer due its complexity when more sources of electricity and/or heat are concerned. On the other hand, simplified models fail from different reasons – oversimplifications often can lead to non-significant results, hence practical evaluation of model results is essential.

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